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Effect of Tube Length on the Performance of Cooling Necklace with Vortex Tube Cold Flow Generator

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EFFECT OF TUBE LENGTH ON THE PERFORMANCE OF COOLING NECKLACE WITH VORTEX TUBE COLD FLOW GENERATOR

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ABSTRACT

The vortex tube, a compact and eco-friendly device, can generate both low-temperature cold flow and high-temperature hot flow from a room-temperature compressed gas supply. Despite its potential, there has been limited research on its application as a cooling device, particularly in the context of a cooling necklace. This study aims to fill this gap by examining the performance of the vortex tube under various conditions. The experiment was conducted indoors, with tube lengths ranging from 60 cm to 140 cm and inlet pressures from 0.2 MPa to 0.4 MPa. The results suggest that an inlet pressure of 0.4 MPa and a tube length of 60 cm are optimal for achieving the lowest temperature cold flow and minimizing heat transfer effects between the cold flow and the environment.

Keywords: Vortex tube; tube length; inlet pressure; heat transfer

INTRODUCTION

A vortex tube is a simple, stationary tool that can create cold and hot flows from a compressed gas at ambient temperature. Vortex tube is capable of producing a cold flow of -50°C and a hot flow up to 255°C. [1]. Vortex tubes' considerable cooling capacity and ease of use due to the absence of moving components serve as their main functions. Uni-flow vortex tubes and counter-flow vortex tubes are the two different kinds of vortex tubes. [2]. According to the investigation, counter flow produces superior results to uni-flow vortex tubes. Figure 1 depicts the flow process inside the vortex tube [3]. When the compressed gas injected through the inlet nozzle, a strong swirl of a gas stream is created in the centre and induces a high-speed rotation of the fluid flow [4]. A heated flow exits the tube as the powerful swirl near the tube's edge runs to its end. A central orifice located close to the entrance nozzle allows the flow in the tube's core to counterflow to the injection point and exit as a cold flow. [5]. The compression and expansion of fluid in the vortex tube produces a temperature-separating effect. The Ranque effect is when two flows of compressed gas from a vortex tube move at different temperatures. [6].

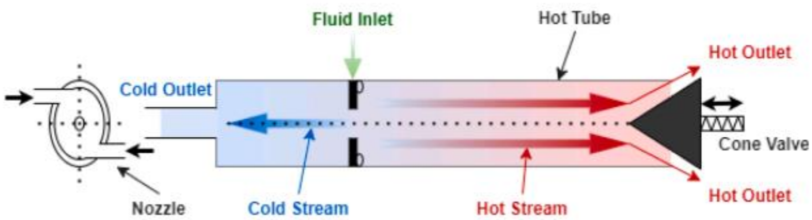


Figure 1 Flow mechanism of hot and cold flows inside vortex tube [3].

The vortex tube is desirable for many cooling applications in the industries, despite its simplicity, low efficiency, low cost, and absence of moving parts, which results in no maintenance. Examples of these applications include cooling CNC machine equipment [7], producing ice [8], microelectronic components [9], cooling CCTV cameras [10], and other real-world uses like DNA amplification [11].

Stable core temperature is essential for the proper and optimal function of a human body. The process of maintaining the human body core temperature is known as thermoregulation [12].The human body contains its own mechanism to regulate body temperature which is through perspiration or sweating [13]. The evaporation process of sweat which occurs from the skin surface into the surrounding environment cools the body. This cooling effect achieves through the concept of heat transfer, that is the latent heat of evaporation of water [14]. The heat transfers between the environment and the human body can occur through radiation, conduction and convection as shown in Figure 2. For a human being, the amount of heat exchanged through conduction is normally minimal, and at rest, it accounts for no more than 3% of body heat loss [15]. Furthermore, convection is the transfer of heat through a moving medium such as gas or liquid.

A stable core temperature is necessary for a human body to function properly and at its best. Thermoregulation is the process of keeping the body's internal temperature constant [12]. The human body has a built-in system to control body temperature, and that system involves sweating or perspiration [13]. The body cools itself as a result of sweat evaporating from the skin's surface into the environment. This cooling effect is accomplished using the concept of heat transfer, namely the latent heat of water evaporation [14]. Figure 2 illustrates how radiation, conduction, and convection can transfer heat between the human body and the environment. The amount of heat exchanged through conduction for a human person is typically negligible, and at rest, it contributes to no more than 3% of total body heat loss [15]. In addition, convection is the transmission of heat through a fluid or gas that is moving.

The use of a traditional refrigeration system is one of the components of daily life in current technological age. The traditional refrigeration system, including air conditioners, home refrigerators, and industrial freezers, is commonly utilized in particular for cooling purposes. To achieve thermal comfort for people, the air conditioner is frequently used to create a thermal environment or surrounding [16]. For a human to maintain comfort or attain thermal comfort, the typical skin temperature is around 30°C [17]. The conventional refrigeration system is well-known for its high efficiency to achieve thermal comfort on human, but also its adverse effects on the environment [18].

It is crucial for the human body to maintain a steady core temperature when the weather is hot. Hyperthermia is caused by the increased body temperature and may interfere with a person's ability to operate at their best [19]. The cooling jacket is an example of a personal cooling system. The military, firefighters, welders, and other hazardous-duty professionals are potential users of such devices. A heat stroke is one of the main effects of bodily overheating. The individual can suffer from a central nervous system collapse [20]. Using the cooling jacket, a thermal comfort is obtained by the user to prevent the heat stroke.

From these studies on gaining thermal comfort, it is unclear from the findings whether the cooling necklace of the vortex tube is efficient at different parameters. The vortex tube's performance as a clod flow source for the cooling necklace at various tube lengths connecting the vortex tube and the cooling necklace, will be assessed in this study.

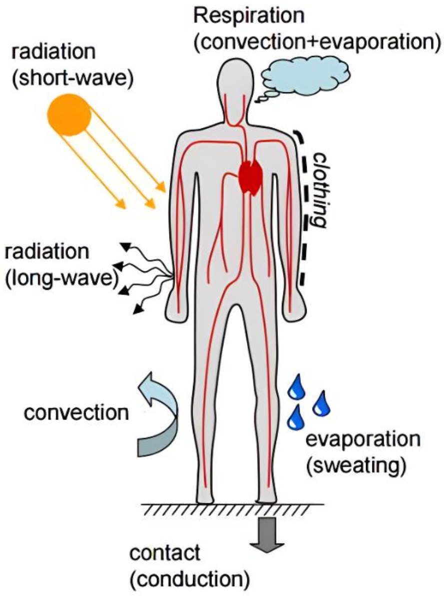


Figure 2 Heat transfer between human body and the environment [21].

METHODOLOGY

Temperature difference

The temperature difference between the entrance air and the cold exit air is known as the inlet-cold temperature difference, or ΔT_{cold}. Conversely, the hot-inlet temperature difference (hot-inlet temperature difference, abbreviated ΔT_{hot}) is defined as the temperature difference between the hot exit air temperature and the inlet air temperature.

$$\Delta T_{cold} = T_{inlet} - T_{cold} \quad 2.1$$

$$\Delta T_{hot} = T_{hot} - T_{inlet} \quad 2.2$$

where T_{inlet} represents for the temperature of the inlet air, T_{cold} for the temperature of the cold exit air, and T_{hot} for the temperature of the hot exit air. The performance of the vortex tube is often determined by the total temperature differential, or ΔT, which separates the effects of heating and cooling [22]. The total temperature difference, ΔT can be obtained as follows:

$$\Delta T = T_{hot} - T_{cold} \quad 2.3$$

Figure 3 illustrates the schematic diagram of the experimental setup.

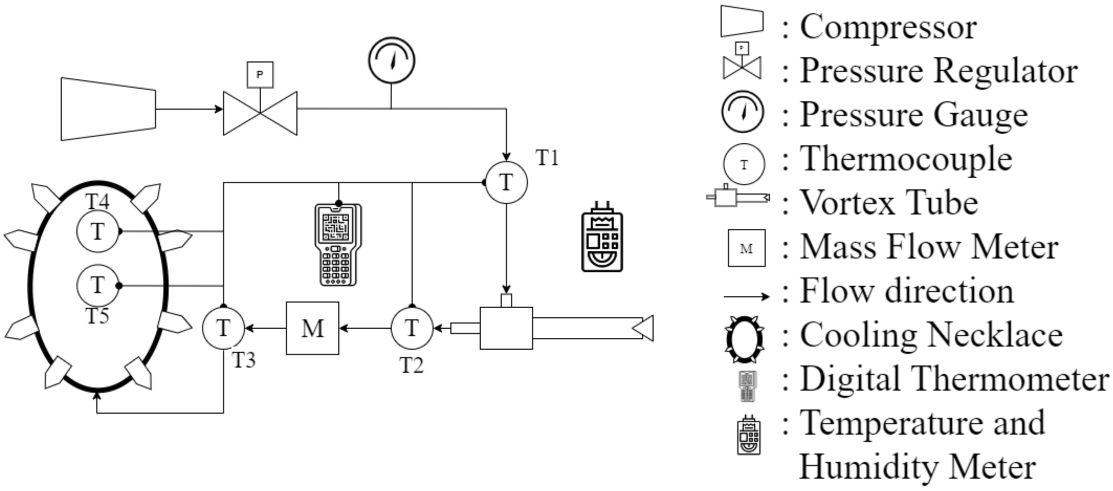


Figure 3 Schematic diagram of experimental setup

The experimental setup consists of a compressor to produce compressed gas, pressure regulator with pressure gauge to regulate the inlet pressure, thermocouple to measure the flow temperature, vortex tube to produce clod flow, mass flow metre to measure the mass flow rate of the inlet and outlet of the vortex tube, and cooling necklace that supplies the clod flow to the user. The aluminium vortex tube is 145mm in length overall. It comprises of an 80mm long tube with an 8mm inner diameter, a cold exit with an 8mm diameter, and a hot exit. The cooling necklace was built with 8 nozzles, to ensure the clod flow is delivered in all direction on the body. During the test, air compressor produces compressed gas and released it through a pressure regulator with a pressure gauge, a thermocouple, and the inlet nozzle at a specific inlet pressure before entering the vortex tube. Two flows are generated inside the tube, one with low temperature and the other with high temperature, inside the vortex tube. The high temperature hot flow escaped to the end of the hot tube fitted with the control valve, while the low temperature clod flow exited the vortex tube through the cold flow exit near the inlet nozzle. The cone-shaped valve, which serves as a control valve, was used to modify the cold mass fraction. Before injecting clod flow into the cooling necklace, the mass flow rate is first measured using a flowmeter. A digital thermometer was used to measure and record all the temperature data using Type-K thermocouples. Each thermocouple point (T1–5) has a label in the figure that indicates the temperature readings that can be retrieved there. The flow temperature at the vortex tube's entrance is T1. T2 is the temperature of the cold flow at the cold flow exit. T3 is the flow temperature of the cold flow before entering the cooling necklace. T4 is the temperature at the chest, while T5 is the temperature at the back of the body. Figure 4 shows the actual experimental setup with a user wearing the cooling necklace. It should be noted that the cooling necklace should be wear inside the jacket. The cooling necklace with exit nozzles is shown in Figure 5. One of the nozzles is used to connect the cooling necklace to the vortex tube. The other 8 nozzles are used to deliver the clod flow from the vortex tube to the front and the back of the body. Additionally, the relative humidity and ambient temperature was measured using a temperature and humidity meter. The experiments took place indoors. For each experiment, temperature readings are taken every two minutes throughout a 20-minute period. The cold mass ratio between the inlet flow and cold flow is kept constant at 0.5.

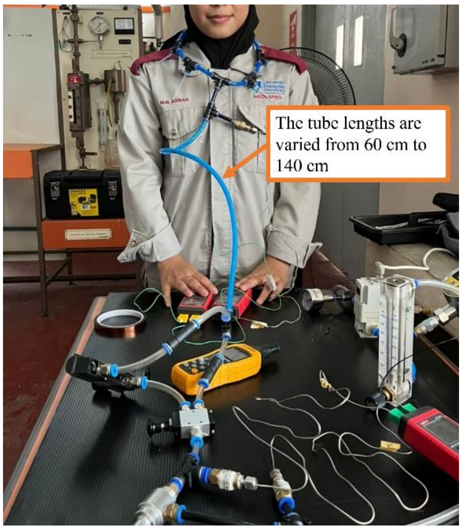


Figure 4 Actual experimental setup

Figure 5 Cooling necklace

Table 1. The experimental conditions

Inlet pressure (gauge pressure), P_{inlet} [kPa]	Tube length, L [cm]
200	60, 80, 100, 120, 140
300	60, 80, 100, 120, 140
400	60, 80, 100, 120, 140

The experiment is conducted with 60 cm, 80 cm, 100 cm, 120 cm and 140 cm of tube length that connect the vortex tube and the cooling necklace. The inlet pressures vary from 0.2 to 0.4 MPa of gauge pressure. The cold mass flow rate is set to constant at 0.5.

RESULTS AND DISCUSSION

Performance of Vortex Tube

Figure 6 illustrates the relationship between the average inlet-cold temperature difference (ΔT) and the inlet pressure (P_{inlet}), across various tube lengths. It is evident from the figure that ΔT increases as the pressure rises.

Interestingly, at a tube length of 100 cm, the temperature difference is slightly higher than the rest at P_{inlet} of 0.2 and 0.3 MPa. However, these differences are minimal (less than 2°C) and can be considered negligible for most practical purposes.

The vortex tube exhibits optimal performance at a pressure of 0.4 MPa and a tube length of 60 cm, where the average ΔT reaches 35.02°C. This suggests that a higher pressure induces a greater swirl velocity within the vortex tube chamber, leading to a decrease in temperature at the center of the tube. This temperature drop is likely due to the expansion of compressed gas, which results in a decrease in pressure.

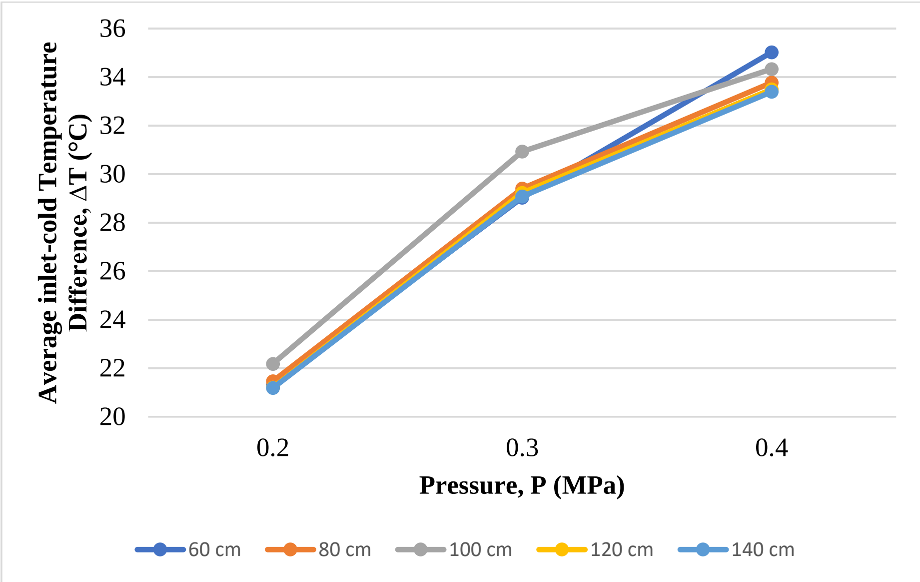
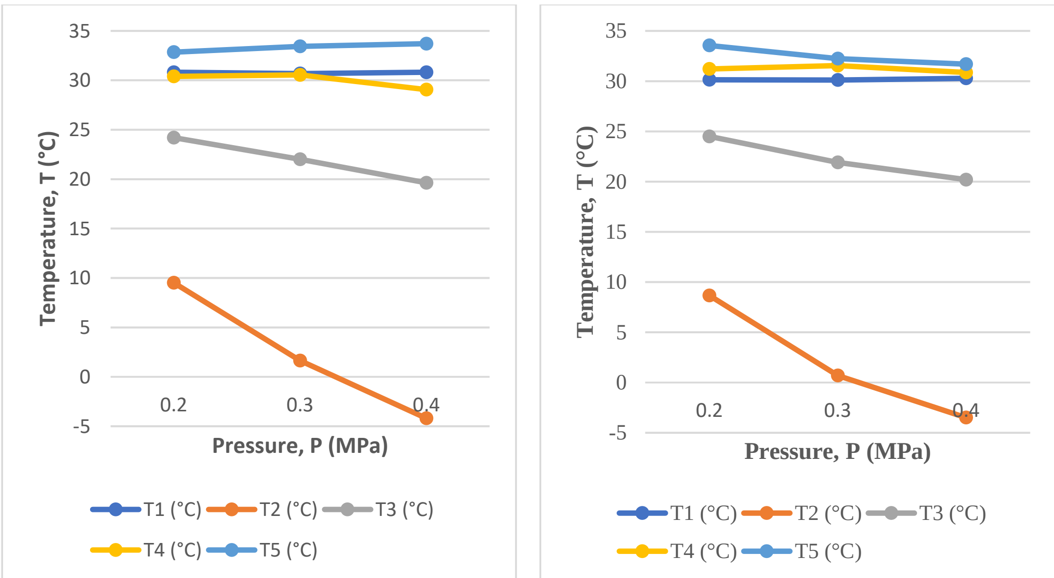
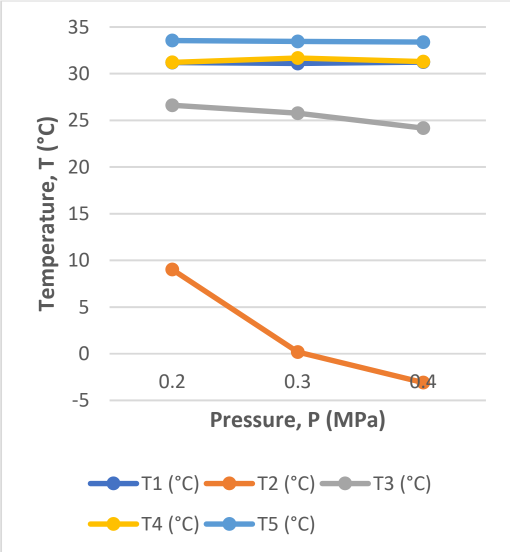


Figure 6 Average inlet-cold temperature difference, $\Delta T = T_{inlet} - T_{cold}$ against pressure, P with different length of tube.

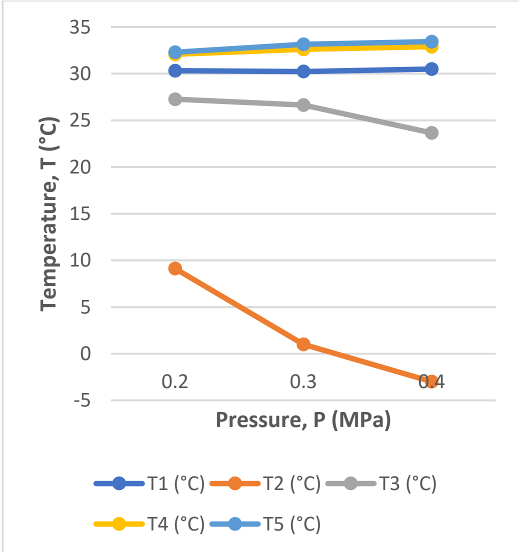
Effect of tube length



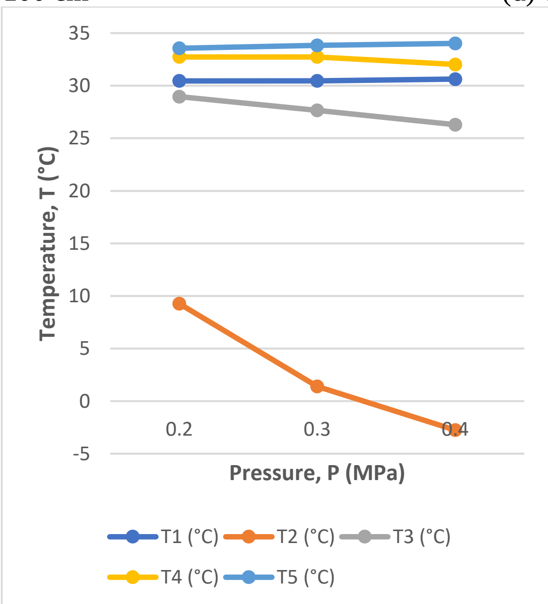
(a) 60 cm (b) 80 cm



(c) 100 cm



(d) 120 cm



(e) 140 cm

Figure 7 Measured temperature at tube length (a) 60 cm, (b) 80 cm, (c) 100 cm, (d) 120 cm, (e) 140 cm

Figure 7 provides a comprehensive analysis of the temperature measurements at various points (T1-5) along different lengths (60, 80, 100, 120, and 140 cm). T1 denotes the temperature of the compressed gas prior to its entry into the vortex tube. The data indicates that regardless of the length of the tube, the inlet temperatures remain consistent. This consistency suggests that the initial conditions of the gas entering the vortex tube are stable and do not significantly vary with the length of the tube.

T2 is indicative of the cold flow temperature as it exits the vortex tube. A comparison between T1 and T2 reveals that the vortex tube has a significant cooling effect on the gas, reducing its temperature by 12°C to 32°C. This demonstrates the effectiveness of the vortex tube in cooling down the gas.

T3 represents the temperature of the cold flow before it enters the cooling necklace. Interestingly, despite exiting from a cooling process in the vortex tube, there is an increase in temperature observed at T3 under all conditions. This could be due to heat absorption from surroundings or due to pressure changes as mentioned earlier.

Finally, T4 and T5 represent temperatures at different points on the body - front and back respectively. These measurements could provide insights into how effectively the cooling necklace is able to distribute and maintain cool temperatures across different parts of the body.

These figures illustrate a clear relationship between the inlet pressure and the cold flow temperature. As the inlet pressure increases, the cold flow temperature decreases. This can be attributed to an increase in swirl velocity within the vortex tube, leading to a more significant expansion of the compressed gas. This expansion process is endothermic, meaning it absorbs heat, which results in a decrease in temperature.

When the cold flow moves from the vortex tube to the cooling necklace, there is a notable increase in temperature, almost up to 20°C. This could be due to heat transfer between the ambient environment and the cold flow within the tube. The ambient heat is absorbed by the cold flow, resulting in an increase in its temperature.

Despite this increase, the temperatures measured at T4 and T5 (front and back of the body) are still lower than normal body temperature. This suggests that even with heat absorption from surroundings, cooling necklace is effective in maintaining a temperature lower than body temperature. Therefore, users of cooling necklace can achieve thermal comfort as their body is not overheated.

However, it’s important to consider that these results might vary based on different environmental conditions and individual body responses. Further studies could be conducted to optimize the performance of cooling necklace under various conditions.

CONCLUSIONS

The research conducted in this study provides an in-depth examination of the cooling potential of the vortex tube. The findings suggest that a substantial decrease in the temperature of the cold flow can be achieved by increasing the inlet pressure from 0.2 MPa to 0.4 MPa (gauge pressure). Additionally, a higher inlet pressure results in a larger volume of cold flow, which can be effectively utilized by the cooling necklace. However, an interesting observation was made regarding the temperature difference between the cold flow at the vortex tube’s exit and at the cooling necklace’s entrance. The latter was found to be higher, which could be due to heat transfer between the cold flow within the tube and its surrounding environment. The study concludes that for optimal cooling efficiency, a tube length of 60 cm and an inlet pressure of 0.4 MPa are most effective. These insights could prove invaluable for future endeavors aimed at designing and optimizing cooling devices that employ vortex tubes. Further investigations could focus on strategies to minimize heat transfer within the tube, such as insulation, to enhance the overall cooling effect.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Nur Shuhada Adnan and Wan Nur Adibah Wan Hisamudin: Conceptualization, Methodology, Writing-Original draft preparation. Muhammad Fadhli Suhaimi: Writing-Reviewing and Editing. Mohd Hazwan Yusof: Visualization, Supervision, Validation, Writing- Reviewing and Editing.

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